

ENVIRONMENT OF THE GAMMA-RAY BURST GRB971214 : A GIANT H II REGION SURROUNDED BY A GALACTIC SUPERSHELL

SANG-HYEON AHN

Department of Astronomy, Seoul National University
San 56-1 Shillim-dong Kwanak-gu, Seoul, Korea

Submitted to ApJ Letters

ABSTRACT

Among a number of gamma ray bursts whose host galaxies are known, GRB971214 stands out for its high redshift $z \geq 3$ and the Ly α emission line having a P-Cygni type profile, which is interpreted to be a direct consequence of the expanding supershell. From a profile fitting analysis we estimate the expansion velocity of the supershell $v_{exp} = 1500 \text{ km s}^{-1}$ and the neutral column density $N_{HI} = 10^{20} \text{ cm}^{-2}$. The redshift $z = 3.418$ of the host galaxy proposed by Kulkarni et al. (1998) has been revised to be $z = 3.425$ from our profile analysis.

The observed Ly α profile is fitted well by a Gaussian curve, which yields the Ly α luminosity $L_{Ly\alpha} = (1.8 \pm 0.8) \times 10^{42} \text{ ergs s}^{-1}$. Assuming that the photon source is a giant H II region, we deduce the electron number density in the H II region $n_e = (40 \pm 10)(\frac{L}{L_{Ly\alpha}})^{0.5}(\frac{R}{100 \text{ pc}})^{-1.5} \text{ cm}^{-3}$, which corresponds to the illumination by about 10^4 O5 stars. We estimate the star-formation rate to be $R_{SF} = (7 \pm 3)\text{M}_\odot \text{ yr}^{-1}$ with the internal and the Galactic extinction corrected.

The theory on the evolution of supernova remnants is used to propose that the supershell is at the adiabatic phase, with its radius $R = 18 E_{53}^{1/2} \text{ pc}$, its age $t = 4.7 \times 10^3 E_{53}^{1/2} \text{ yrs}$, and the density of the ambient medium $n_1 = 5.4 E_{53}^{-1/2} \text{ cm}^{-3}$, where $E_{53} = E/10^{53} \text{ ergs}$. And we estimate the kinetic energy of the supershell to be $E_k = 7.3 \times 10^{52} E_{53} \text{ ergs}$. These values are consistent with the hypothesis that the supershell is the remnant of a gamma ray burst.

We note similarities between supershells found in nearby galaxies and remote primeval galaxies, and propose that the gamma ray burst may have occurred in a giant H II region whose environment is similar to in star forming galaxies.

Subject headings: gamma rays: bursts — galaxies: individual (GRB971214) — galaxies: starburst — line: profiles

1. INTRODUCTION

Gamma ray bursts (hereafter GRBs), located at cosmological distances, form a group of the most luminous objects in the Universe. A number of GRBs were observed with their host galaxies, of which intensive spectroscopic and imaging observations have been performed using the Hubble Space Telescope and the Keck telescopes. GRB971214 is one of such objects with a very high redshift $z > 3$ and also is worth a particular attention in following points.

Firstly, even after the optical transient region had faded away, we can marginally detect a bright spot in the HST image, and the continuum and emission line fluxes from this spot overwhelm those from the remaining part of the host galaxy. Secondly, the ultraviolet spectrum of GRB971214 illustrated in Fig. 1 shows a flat UV continuum which is often found in star forming galaxies. In addition, the Ly α emission line has a black absorption trough in the red part of the emission peak. These facts imply that the UV spectrum is formed in a star forming region which is surrounded by a thick and expanding medium of neutral hydrogens. We note that the location of the GRB afterglow coincides with the star forming region or the bright spot, which leads to the proposal that the GRB occurs in a star forming region, and in this Letter we deduce the physical environment of the GRB from its spectrum.

The P-Cygni type Ly α emission in the spectrum of primeval galaxies has been often attributed to an absorption effect by a galaxy not associated with the primeval galaxy but intervening accidentally in the line of sight. It has been regarded as a

damped Ly α absorption that occurs in the vicinity of the source galaxy. In order to check this possibility, we calculate the probability for observing an intervening galaxy in front of the GRB host galaxy, which is none other than the optical depth for seeing a galaxy between the GRB host galaxy at $z = 3.425$ and the place that corresponds to v_{exp} in the Hubble's expansion law. The optical depth is simply expressed by

$$\tau = n_g(1+z)^3\sigma L, \quad (1)$$

where the comoving volume number density of normal galaxies at $z = 0$, $n_g \sim 0.02h^3 \text{ Mpc}^{-3}$ (Im 1995), and the path length L is estimated to be $L = v_{exp}/H$ with H being the Hubble constant at the redshift and given by

$$H = H_0[\Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}, \quad (2)$$

where the cosmological density parameters are $\Omega_M = 8\pi G\rho_0/3H_0^2$, $\Omega_\Lambda = \Lambda/3H_0^2$, and the Hubble parameter $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Here, the cross section is given by $\sigma = \pi(r_{10}10h^{-1} \text{ kpc})^2$, where r_{10} is the typical galaxy size in units of 10 kpc. A direct substitution yields the optical depth $\tau = 0.0023r_{10}^2$ for $\Omega_M = 1/3$ and $\Omega_\Lambda = 2/3$, and $\tau = 0.0025r_{10}^2$ for $\Omega_M = 0.3$ and $\Omega_\Lambda = 0$. This indicates that if the average size of galaxies at $z \approx 3$ is not large, then it is highly improbable that the damped absorption in the spectrum of host galaxy of GRB971214 is formed by a galaxy intervening accidentally.

This leaves us to consider an alternative hypothesis, according to which the P-Cygni type profile of Ly α is formed by the the expanding supershell that surrounds the star forming

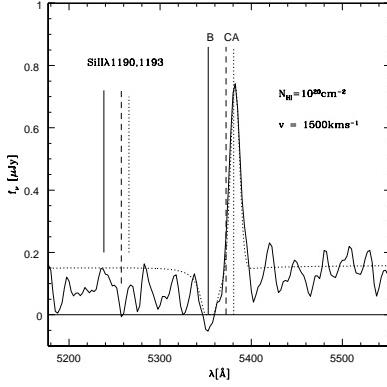


FIG. 1.— Profile of the Ly α emission line and its P-Cygni type absorption (solid line) with the best fit profile (dotted line). The emission has a Gaussian profile whose width is 5.0, line center flux $f(\lambda = 5380.8) = 0.675 \mu\text{Jy}$. The line center frequency $\lambda = 5380.8$ gives $z = 3.425$. The P-Cygni type absorption is best fitted by the column density of the supershell $N_{\text{HI}} = 10^{20} \text{ cm}^{-2}$ and the expansion velocity $v_{\text{exp}} = 1500 \text{ km s}^{-1}$. The dotted vertical line denoted by 'A' is the solid line center of our result, the line denoted by B is the location of the P-Cygni absorption trough, and the 'C' vertical line is provided by Kulkarni et al. (1998). Comparing with Ly α we also show SiIIλ1190 line, but the S/N ratio is not good.

region in GRB971214 and is the remnant of the GRB precedent to GRB971214. In order to check this possibility, we now calculate a number of GRB event in a galaxy at $z \approx 3.4$. Assuming the supernova rate is proportional to the star-forming rate, Sadat et al. (1998) calculated the supernova rate at $z \approx 3.4$, $\Gamma_{\text{SN}} \simeq 0.011 \times 10^6 h_{65}^3 \text{ SNe Myr}^{-1} \text{ Mpc}^{-3}$, where $H_0 = 65 h_{65} \text{ km s}^{-1} \text{ Mpc}^{-1}$. Accepting the concept that the GRB rate traces the massive star formation rate, Woods & Loeb (1998) showed $\Gamma_{\text{GRB}} \simeq 10^{-6} \Gamma_{\text{SN}}$, where $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65 h_{65} \text{ km s}^{-1} \text{ Mpc}^{-1}$. Therefore, $\Gamma_{\text{GRB}}(z \approx 3.4) \simeq 0.011 h_{65}^3 \text{ Myr}^{-1} \text{ Mpc}^{-3}$. Adopting the number density of galaxies at $2.0 < z < 3.5$, $\Phi^* = 1.76 \times 10^{-3} h_{65}^3 \text{ Mpc}^{-3}$ (Pozzetti et al. 1998), we can get the GRB rate per a galaxy at $z \approx 3.4$, $\Gamma_{\text{GRB}} \simeq 6 \text{ Myr}^{-1}$. Therefore, the number of GRB events per a galaxy during 10^{4-5} yrs is $N_{\text{GRB}} = 0.06 \sim 0.6$. Moreover, the beaming factor, if exists, can increase the event rate by another factor of ten and the number of GRB events per a galaxy during 10^{4-5} yrs is $N_{\text{GRB}} = 0.6 \sim 6$, which makes our supershell hypothesis more probable and alternative suggestion.

It is noticeable that the similar P-Cygni features are observed in primeval galaxies and nearby star forming galaxies. Lee and Ahn (1998) proposed that the features might be caused not by an overlapping intergalactic medium but by the expanding medium enveloping the star forming region in the galaxies. And this concept may be applied to such a remote star-forming galaxy as the host galaxy of GRB971214. However, we can not exclude the possibility that the multiple supernovae explosion may also result in the expanding shell.

In this Letter, we adopt the hypothesis of GRB-driven supershell and perform a profile fitting analysis to derive physical parameters characterizing the expanding supershell of neutral hydrogens surrounding the star forming region of the GRB host galaxy.

2. IMAGES AND SPECTRUM OF GRB971214

GRB971214 was detected at 9 UT, December 14, 1997 (Heise et al. 1997), and its optical counterpart twelve hours after the burst (Halpern et al. 1998). With a total fluence of $1.09 \times 10^{-5} \text{ ergs cm}^{-2}$ (Kippen et al. 1997) and the measured redshift of $z = 3.418$ (Kulkarni et al. 1998), its energy

release is estimated to be $\sim 3 \times 10^{53} \text{ ergs}$ in γ -rays alone under the assumption of isotropic emission, $\Omega_0 = 0.3$, and $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

In Fig. 1 is shown its ultraviolet spectrum redshifted to the optical band and obtained by Kulkarni et al. (1998) using the Keck telescope. It is characterized by a flat UV continuum that is typically found in the spectra of star forming regions. It is also seen that the Ly α emission has a P-Cygni type profile, which is frequently observed in the astronomical objects near or far (Lee & Ahn 1998). Lee and Ahn (1998) proposed that the P-Cygni type Ly α line is formed when the Ly α photons emitted in the central super star-cluster are radiatively transferred in a HI supershell that are optically thick and expanding.

In this work, the photon source is assumed to be the H II region that may contain 10^4 O stars. According to Marlowe et al. (1995), nearby starbursting dwarfs are inferred to contain a similar number of OB stars, when considering H α luminosity. So this can be thought to be neither entirely new nor extreme assumption for galaxies of higher redshifts. Furthermore, it appears less plausible that the Ly α emission arises from the medium ionized by shocks produced by supernovae or hypernovae. This is because the number density of the inner region is not sufficiently high to give the recombination time scale $\leq 10^5$ years.

3. IS THE PHOTON SOURCE SURROUNDED BY THE GRB REMNANT?

3.1. Interpretation of the P-Cygni Absorption

In this work we will consider the shell hypothesis, and derive the physical properties of the expanding neutral medium from the observed Ly α absorption.

We assume a Gaussian profile for the unobscured Ly α emission and convolve it with a Voigt function with the center displaced by the expanding velocity that will be determined by the fitting procedure. In principle, the effect of the frequency redistribution by back-scatterings should be considered. However, we neglect this effect in this paper, because the S/N ratio and the resolution of the spectrum are not sufficiently good. For the continuum level, the blue part of Ly α , which is more prone to extinction, is extrapolated from the red portion of the spectrum

given by Kulkarni et al. (1998). They quote $F_\nu = 174(\nu/\nu_R)^\alpha$ nJy with $\alpha = -0.7 \pm 0.2$, where F_ν is the spectral density at frequency ν and $\nu_R = 4.7 \times 10^{14}$ Hz, the central frequency of the R band.

We show the result in Fig. 1, where the dotted line represents the best fit profile, the solid line the observed profile, and the horizontal solid line the continuum level. The best fit expansion velocity of the supershell relative to the H II region is determined to be $v_{exp} = 1500$ km s $^{-1}$, and the best fit line center optical depth $\tau_0 = 6 \times 10^6$, which corresponds to $N_{HI} = 10^{20}$ cm $^{-2}$. The best fit Ly α profile has the width of $\sigma = 5$ and the line center flux $f(\lambda = 5280.8)$ = 0.675 μ Jy, which gives the unobscured flux to be 9.1×10^{-18} erg cm $^{-2}$ s $^{-1}$ and the systemic redshift $z = 3.425$.

This is slightly larger than the redshift proposed by Kulkarni et al. (1998), who may have overestimated the absorption in the blue part of the Ly α . However, the absorption trough is sufficiently remote from the line center in the velocity space only to erode the extreme blue part of the Ly α emission. Hence, we prefer the redshift of $z = 3.425$ of GRB971214 to the redshift of $z = 3.418$, and subsequently other physical parameters need to be revised.

Assuming a standard Friedman cosmology with $H_0 = 65$ km s $^{-1}$ Mpc $^{-1}$ and $\Omega_0 = 0.3$, the luminosity distance $d_L = 9.7 \times 10^{28}$ cm. Considering the Galactic extinction, the unobscured Ly α flux is corrected to be $F_{Ly\alpha} = (1.5 \pm 0.7) \times 10^{-17}$ erg cm $^{-2}$ s $^{-1}$, where the observational error given by Kulkarni et al. (1998) is introduced. Therefore, for the assumed cosmology, the Ly α line luminosity $L_{Ly\alpha} = (1.8 \pm 0.8) \times 10^{42}$ erg s $^{-1}$. If there is no internal extinction in the interior of the Ly α source, this corresponds to $n_e = (1.4 \pm 0.4)(\frac{L}{L_{Ly\alpha}})^{0.5}(\frac{R}{1\text{kpc}})^{-1.5}$ cm $^{-3}$ or $n_e = (40 \pm 10)(\frac{L}{L_{Ly\alpha}})^{0.5}(\frac{R}{100\text{pc}})^{-1.5}$ cm $^{-3}$, of which the ionization can be maintained by $\sim 10^4$ O5 stars as the ionizing source.

From the Ly α luminosity, we can estimate the star-formation rate (Thompson, Djorgovski, & Trauger 1995) to be $R_{SF} = (7 \pm 3)\text{M}_\odot \text{ yr}^{-1}$, with both the internal and the Galactic extinction being corrected. This is consistent with the star forming rate given by Kulkarni et al. (1998) as a lower limit, $R_{SF} = 5.2 \text{ M}_\odot \text{ yr}^{-1}$ which was obtained from the rest-frame con-

tinuum luminosity at 1,500 .

Using the revised redshift of the GRB host galaxy, we refine other absorption lines in the observed spectrum. In Fig. 2, we show the spectrum of the GRB host in the UV regime. It is seen that the revised wavelengths are in good agreement with the absorption features.

3.2. Physical Configuration of the Supershell

We consider the dynamical evolutionary model of the supernova remnant to derive the physical quantities of the shell. According to Woltjer (1972), the supernova remnant has four evolutionary phases, that is, the free expansion phase, the Sedov-Taylor or adiabatic phase, the snowplow or radiative phase, and finally the merging or dissipation phase (see also Reynolds 1988).

According to Woltjer(1972), the radiative phase begins roughly when the expansion velocity of the shell becomes

$$v = 300 \left(\frac{n_1}{1 \text{ cm}^{-3}} \right)^{2/17} \left(\frac{E}{10^{53} \text{ ergs}} \right)^{1/17} \text{ km s}^{-1}, \quad (3)$$

where n_1 is the number density of the ambient medium and E is the initial explosion energy. Since the expansion velocity $v = v_{exp} = 1500$ km s $^{-1}$ of the supershell exceeds the velocity in the radiative phase by a large margin, we propose that the supershell is in the adiabatic phase, which is described by the Sedov solution.

According to the Sedov solution in a uniform medium of number density n_1 in which we have the relation $n_1 = 3N/R$,

$$R = 0.92 \left(\frac{E}{m_H N} \right)^{1/4} t^{1/2} \text{ cm}, \quad (4)$$

$$v = 0.37 \left(\frac{E}{m_H N} \right)^{1/4} t^{-1/2} \text{ cm s}^{-1}, \quad (5)$$

$$n_1 = 3.2 \left(\frac{m_H N^5}{E} \right)^{1/4} t^{-1/2} \text{ cm}^{-3}, \quad (6)$$

where v is the expansion velocity of the supershell, R the size of the supershell, E the initial explosion energy, N the column density of the supershell, m_H the hydrogen mass, and t the age of the shell.

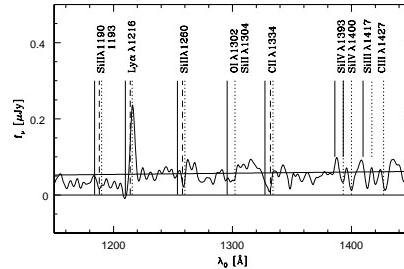


FIG. 2.— UV spectrum of the GRB971214 which is smoothed by a Gaussian kernel with its width $\sigma = 5$. Solid horizontal line stands for the continuum level, the solid vertical bars represent the line centers whose velocity components correspond to the Ly α absorption. The refined absorption centers which correspond to the systemic redshift of the GRB host are presented by the dotted vertical lines. The dashed vertical bars stand for the absorption lines suggested by Kulkarni et al. (1998) The transitions for the absorption are also denoted.

Using the values $v = v_{exp} = 1500 \text{ km s}^{-1}$ and $N = 10^{20} \text{ cm}^{-2}$, we get

$$t = 4.7 \times 10^3 \left(\frac{E_{53}}{N_{20}} \right)^{1/2} \text{ yrs}, \quad (7)$$

$$R = 18 \left(\frac{E_{53}}{N_{20}} \right)^{1/2} \text{ pc}, \quad (8)$$

$$n_1 = 5.4 \left(\frac{N_{20}^3}{E_{53}} \right)^{1/2} \text{ cm}^{-3}, \quad (9)$$

where $N_{20} = N/10^{20} \text{ cm}^{-2}$ and $E_{53} = E/10^{53} \text{ ergs}$.

In Fig. 3 are shown the size and age of the supershell as well as the volume number density of the ambient medium with E_{53} being a free parameter. For a range of input energy, $0.01 \leq E_{53} \leq 100$, we get the possible range of the other parameters $0.53 \leq n_1 \leq 53$, $2 \text{ pc} \leq R \leq 180 \text{ pc}$, and $5 \times 10^2 \text{ yrs} \leq t \leq 5 \times 10^4 \text{ yrs}$.

From these values we estimate the total kinetic energy of the expanding supershell given by $E_k = 2\pi R^2 N_{HI} m_H v_{exp}^2 = 7.3 \times 10^{52} E_{53} \text{ ergs}$. It is also noticeable that this kinetic energy can be comparable to those of the galactic supershell including those in Our Galaxy, NGC 4631, and M101 (Heiles 1979, Rand & van der Hulst 1993, Wang 1999). Furthermore, the P-Cygni Ly α lines of the primeval galaxies also show the similar energy scale. Thus, we propose that the supershell is the remnant of a hypernova or a GRB that had exploded earlier than GRB971214.

4. SUMMARY AND IMPLICATIONS

We have studied on the formation of P-Cygni type Ly α in the spectrum of GRB971214, and found that there are at least three components in the system, i.e. the parsec scale remnant of GRB971214 itself, a giant H II region, and a supershell surrounding it.

The giant H II region from which Ly α emission originates is photoionized by a super stellar cluster whose total ionizing photons correspond to those emitted from about 10^4 O5 stars. The existence of the P-Cygni type absorption plausibly implies that there exists a supershell surrounding the H II region. By a

profile fitting procedure, we found out that the shell is expanding with a velocity of $v_{exp} = 1500 \text{ km s}^{-1}$ and its neutral column density $N_{HI} = 10^{20} \text{ cm}^{-2}$. We also revised the redshift of the Ly α emission source to be $z = 3.425$, and its unobscured Ly α luminosity to be $L_{Ly\alpha} = (1.8 \pm 0.8) \times 10^{42} \text{ erg s}^{-1}$, which gives a more reasonable star formation rate to be $R_{SF} = (7 \pm 3) M_\odot \text{ yr}^{-1}$.

We also applied the theory on the hydrodynamical evolution of supernova remnants to the supershell surrounding GRB971214. Assuming a reasonable scale of the initial explosion energy of the supershell, we propose that the supershell is at the adiabatic phase, with its radius $R = 18 E_{53}^{1/2} \text{ pc}$, its age $t = 4.7 \times 10^3 E_{53}^{1/2} \text{ yrs}$, and the number density of the ambient medium $n_1 = 5.4 E_{53}^{-1/2} \text{ cm}^{-3}$, where $E_{53} = E/10^{53} \text{ ergs}$. And we estimate the kinetic energy of the supershell to be $E_k = 7.3 \times 10^{52} E_{53} \text{ ergs}$.

It is noticeable that there are many astronomical objects showing the similar characteristics. Using the X-ray data, Wang (1999) has discovered the candidates of GRB remnants in M101, of which two exhibit similar physical characteristics to those of the GRB remnant in GRB971214. With the advent of 10m class telescopes, a large number of primeval galaxies are observed by applying several methods including the Lyman break method (Steidel 1996). About 50 percent of Ly α emission lines in their spectra show P-Cygni type profiles. It is suggested that these profiles are formed in an expanding media surrounding the star forming region and a case study was performed for DLA 2233+131 in detail (Lee & Ahn 1998).

Recently one of the most debated suggestions is the hypernova conjecture, according to which gamma-ray bursts occur in star forming regions. Our results strongly favor this model and more concrete evidence is expected as the sample of GRB spectra showing Ly α emission becomes statistically significant.

The author thanks George Djorgovski and Shri Kulkarni for kindly providing the optical spectrum of GRB971214. He also thanks Bon-Chul Koo, Kee-Tae Kim, Hee-Won Lee, Hwang-Kyung Sung, In-Su Yi, and Hyung-Mok Lee for their invaluable discussions. The author thanks to the anonymous referee for his/her fruitful comments and suggestions.

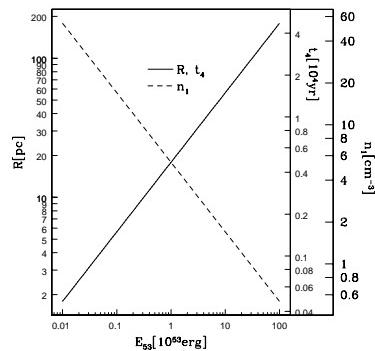


FIG. 3.— Radius(R) in pc, age(t_4) in 10^4 yrs, and the volume number density of the ambient medium(n_1) with the variation of the input energy (E_{53}) in 10^{53} ergs.

REFERENCES

- Heckman, T. M., Carmelle, R., Leitherer, C., Garnett, D. R., & van der Rydt, F. 1998, ApJ, 503, 646
- Heiles, C. 1979, ApJ, 229, 533
- Heise, J., et al. 1997, IAU Circ. No. 6787
- Halpern, J. P., Thorstensen, J. R., Helfand, D. J., & Costa, E. 1998, Nature, 393, 41
- Im, M., 1995, Ph.D. Thesis, the Johns Hopkins Univ.
- Kippen, R. M., 1997, IAU Circ. No. 6789
- Kulkarni, S., et al. 1998, Nature, 393, 35
- Lee, H. -W. & Ahn, S. -H. 1998, ApJ, 504, L61
- Perna, R. & Loeb, A. 1998, ApJ, 503, L35
- Pozzetti, L., et al. 1998, MNRAS, 298, 1133
- Rand, R. J. & van der Hulst, J. M. 1993, AJ, 105, 2098
- Reynolds, S. P. 1988, in chap. 10 of Galactic and Extragalactic Radio Astronomy, 2nd Edition, ed. by Verschuur and Kellermann, Springer-Verlag
- Sadat, R., Blanchard, A., Guideroni, B., & Silk, J. 1998, \AA , 331, L69
- Steidel, C. C., et al. 1996, ApJ, 462, L17
- Tenorio-Tagle, G. & Bodenheimer, P. 1988, ARAA, 26, 145
- Thompson, D., Djorgovski, S., & Trauger, J. 1995, AJ, 110, 963
- Wang, D. Q. 1999, ApJ, 517, L27
- Woods, E. & Loeb, A. 1998, ApJ, 508, 760
- Woltjer, L. 1972, ARAA, 10, 129